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DELAMINATION IDENTIFICATION OF FRP COMPOSITES USING NORMALIZED MODAL CURVATURE

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ABSTRACT

Delamination in FRP composites causes a considerable reduction in the transverse load carrying capacity, which is a major apprehension to the aerospace and automotive industries. Because of comparatively low cost and the flexibility of measurement., modal analysis based damage identification in the composite materials is usefully employed in structural health monitoring. Using Normalized modal curvature the delamination location detection is discussed in this paper. For the intact and delaminated composites numerical modal analysis is performed using ANSYS-ACP. Modal parameters (frequency and mode shape) are extracted from the simulated composite plate. Modal curvature at each node is calculated by double differentiation of mode shape deformation. Damage Index (DI) is formulated using the modal curvature of intact and delaminated composite plates. Analyzing DI at each node of the plate region delamination is identified. The proposed approach is used successfully to identify the delamination position and size of the composites.

KEYWORDS: Composites, Delamination, Finite Element Modal Analysis & Modal Curvature

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Original Article

1. INTRODUCTION

In the current period, composite resources are supplant conservative metals in automotive, civil, aerospace and marine industries. The most significant recompense of the composite materials are relatively low weight, corrosion resistance, and high strength to weight ratio. These composites are however prone to delamination and thus necessitating the early recognition of the flaw before it initiates into a critical fault. Cost-effective and dependable damage discovery is critical for the consumption of composite resources. Health monitoring of such structure is extremely necessary to stop sudden breakdown.

The most common failure modes of composite plates are delamination. Debonding between the adjacent layers at a particular region of the multilayered composite plate is considered as delamination. It reduces the compressive strength of the laminated composites. It takes place inside of the composite layers, so without breaking, it is difficult to identify the delamination existence in the multilayered composites. Hence, the forecast of delamination in composite plates is required during the service time of composites.

Material characterization is one of the important aspects in the design of mechanical components. In general, the elastic constants are determined by destructive tests like tensile, bending, and shearing, etc., but we can also determine the elastic constants by nondestructive tests. Elastic constants are determined by vibration testing[1,2], approximate mathematical equations are formulated between the natural frequencies and elastic constants. The wave decomposition technique [3] is used to compute the whole set of 21elastic stiff nesses of the

composites by measuring the ultrasonic phase velocity through the composite material. Quasi-S and quasi-P [4] waves are incidents with a variety of angles through the material.

Damage identification through numerical analysis, modeling of composites with their damages has played an important role. Composite plates modeled as separate layers and delamination is implemented using 9 noded quadrilateral MITC9 element[5], which is devoid of membrane locking and shear locking. Delamination is also implemented as a separation of 0. 02 mm between the adjust layers[6], and Virtual spring elements[7] are adopted in the area of delamination with less stiffness than other regions.

The modal analysis based singularity(damage) recognition is an efficient method because of its ease of accomplishment, and acquire the global and the local information of the composite structures. Essential efforts are previously committed to developing damage identification algorithms using a vibration-based approach. The parameters used for damage identification using modal analysis are frequencies, mode shapes, damping ratios, modal curvature, and modal strain energy. For first-level Structural Health Monitoring (SHM) natural frequencies [8,11] used because of global nature. Mode shape[9,10] information and its modified form with special algorithms are use to find the second level of SHM, the position of the significant damage in structures. Modal curvatures and modal strain energy are more sensitive at local regions than mode shapes and natural frequencies. Modal curvature [12-18] and its modified forms like change in curvatures, normalized curvatures, modal assurance criteria are used to identify the small-size damages.

Ultrasonic lamb waves[19-21], guided waves[22-23] are used to find the damage center and quantification of the damages like a pinhole, slot, and delamination in the composite plates.

This effort aims to study the characteristics of Modal Curvature (MC), to detect the delamination center in the composite plates. First, Modal Curvature is calculated using mode deformation data of the intact and delaminated plates. The Second, Damage Index (DI) is estimated at each node using normalized modal curvatures. Delamination location and quantification are done using the DI matrix of the composite plate. This method is experimentally validated using an FFT analyzer and accelerometer to acquire the modal curvature through the mode deformation of the intact and delaminated composites.

2. THEORY

The second order differentiation of mode shape $w(x, y)$ of a composite plate is considered as the modal curvature.

$$\kappa = \kappa_{xx} + \kappa_{yy} = \frac{\partial^2 w(x,y)}{\partial x^2} + \frac{\partial^2 w(x,y)}{\partial y^2} \tag{1}$$

Where, κ, κ_{xx} and κ_{yy} are modal curvatures, modal curvature along X-axis and modal curvature along Y-axis respectively.

2.1 Normalized Modal Curvature

The damage factor referred to an as absolute difference of the modal curvatures of the intact with delaminated composite plates. On delamination location, local modal curvature is increased due to the reduction of stiffness of composite plates [12].

Modal Curvature is estimated from mode shape obtained from the finite element and experimental modal analysis by central difference approximation. The modal curvatures in the direction of X-axis and Y axis are obtained mathematically as [12]:

$$\kappa_{xx} = \frac{w_{(i-1),j} - 2w_{i,j} + w_{(i+1),j}}{h^2} \tag{2}$$

$$\kappa_{yy} = \frac{w_{i,(j-1)} - 2w_{i,j} + w_{i,(j+1)}}{h^2} \tag{3}$$

$$\kappa = \kappa_{xx} + \kappa_{yy} \tag{4}$$

where i and j are row and column, $w_{i,j}$ is mode shape value of i^{th} row and j^{th} column composite plate.

The change in modal curvature (CMC) is an absolute difference of modal curvatures of delaminated and intact composite plates:

$$\Delta\kappa_{i,j} = \kappa_{i,j}^{(d)} - \kappa_{i,j}^{(u)} \tag{5}$$

The CMC is calculated through Equation (5), at each grid node of the composite plate and normalized CMC at each node to the same range by the following equation.

$$\Delta\kappa_{i,j} = 1 + \frac{\Delta\kappa_{i,j}}{\max(\Delta\kappa_{i,j}) - \min(\Delta\kappa_{i,j})} \tag{6}$$

This normalized CMC is considered as Damage Index (DI) at each node.

3. MODAL ANALYSIS OF COMPOSITES

3.1 Numerical Modal Analysis

The Glass/epoxy composite plate (120x120x6.8) by stacking sequence $[0°/90°/0°/90°]_s$ was considered for numerical analysis. $20x20mm^2$ delamination area is considered at centre, right and North East positions. The elastic constants of the composites for FEM simulation are E_1 = 44.63 GPa, E_2 =8.46 GPa, E_3 = 8.46 GPa, υ_{12} =0.26, υ_{13} = 0.26, υ_{23} = 0.21, G_{12} =3.23GPa, G_{13} = 3.23 GPa, G_{23} =4.32 GPa, and ρ = 1832 kg/m^3.

The composite plate is modeled using ANSYS- ACP (pre) as per the required stacking sequence and dimensions. Delamination is incorporated in the interface layer as an open area with thickness layer during the modeling of composites. The numerical modal investigation is done on the intact and delaminated composite plates to take out the mode shapes and natural frequencies. Modal curvatures of the first mode are calculated using the first mode shape.

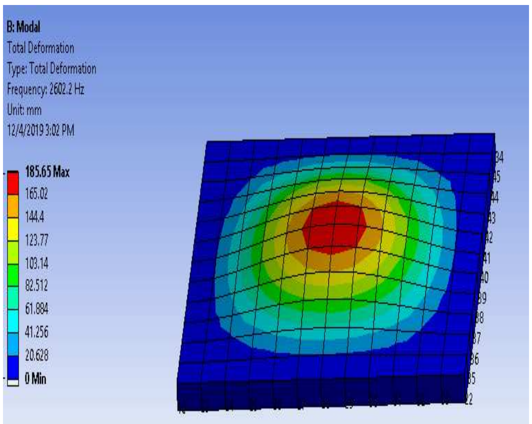


Figure 1: Meshed Model of Delaminated Plate.

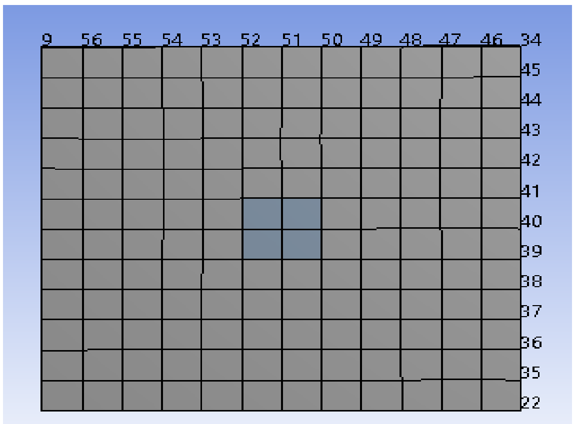


Figure 2: First Mode Shape of Delaminated Plate.

3.2 Experimental Modal Study

The experimentation is done on the cross-ply composites with fiber orientations as $[0/90/0/90]_s$. The composites are prepared by hand lay-up technique. Four composite specimens of dimensions 170 mm×170 mm×6.8mm are fabricated for the experimental work is shown in figure 3, 20x20 mm^2 delamination area is considered at the center, right and northeast positions. Artificial delamination is created by Teflon film tape by a thickness of 25 µm at middle of the plates during the fabrication of composites.

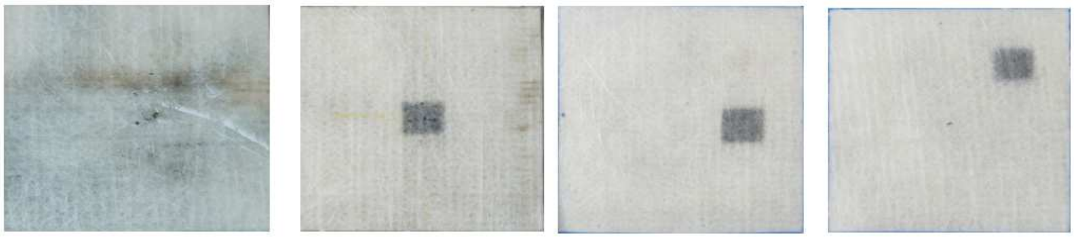


Figure 3: Specimens of Intact and Delamination at three Positions.

Experimental modal analysis is done using FFT Analyzer, accelerometer and impact hammer to extort the natural frequencies & mode shape values of laminated composites with and without delamination by considering 13x13 measuring points, the experimental arrangement is shown in figure 4.

Figure 4: Experimental Setup.

3.3 Experimental Procedure

The experimental procedure is followed for the taking out of the mode shape values and the natural frequencies of composite samples.

- Fasten the specimen as all the edges of the plate are fixed.
- Connect the impact hammer, accelerometer to FFT analyzer properly.
- Glue the accelerometer at the middle of the rear side of the plate.
- Impact hammer is used for the excitation the composite plate.
- Perform vibration test on composite using FFT analyzer and accelerometer.
- The natural frequencies and mode shape values are obtained from Frequency Response Function (FRFs) by identifying the peaks and these frequencies are considered as natural frequencies when the coherence function corresponding to the frequency is greater than 0.9 those values are considered as natural frequencies.

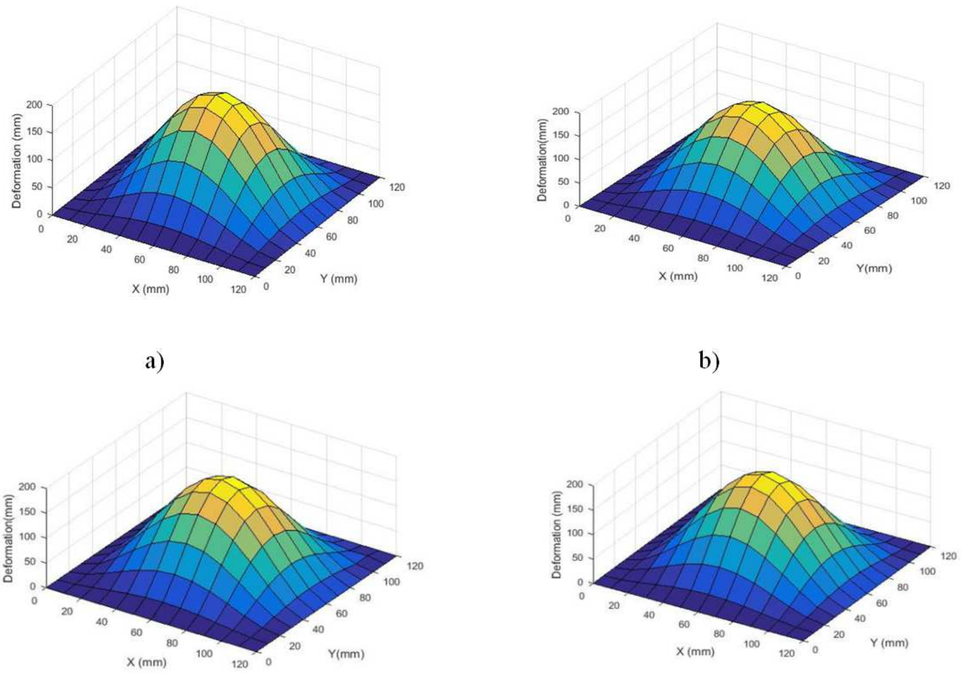
- Replicate the vibration test practice and extract FRF value at each grid point first natural frequencies of the samples.
- Post process is done using EDM software, which is used to extract mode shape value at natural frequency of all the grid points of the composites.

4. RESULTS AND DISCUSSIONS

4.1. Numerical Results

Numerical modal analysis is performed on the eight-layer composite plate with stacking sequence $[0/90/0/90]_s$ using ANSYS -ACP(Pre) software for intact and delaminated plates with three delamination positions at the center, right and NE of 20x20 mm^2 delamination area. The fixed boundary condition is applied for all the edges of the plate in numerical analysis. The first frequency and mode shape are extracted for the intact and delaminated composites by the numerical modal analysis.

The mode shape deformations of the composites are revealed in figure 5. All mode shapes seem to be similar, there no singularity in mode shapes of composite plates, so we can't identify the delamination locations.



a) b) c) d)

Figure 5: Mode Shapes of Composite Plates, (a) Intact (b) Delamination at Center (c) Delamination at Right-sided (d) Delamination at NE Corner.

Modal curvatures of the intact and three delaminated composites are calculated using mathematical equations (2), (3) and (4). The modal curvature plots of intact and three delaminated composites are shown in figure 6. There is a small deviation of the surface at the delamination location, but this deviation is dominated as a result of the global tendency of the modal curvature surface, so this singularity is not sufficient to identify the delamination positions of the composite plates

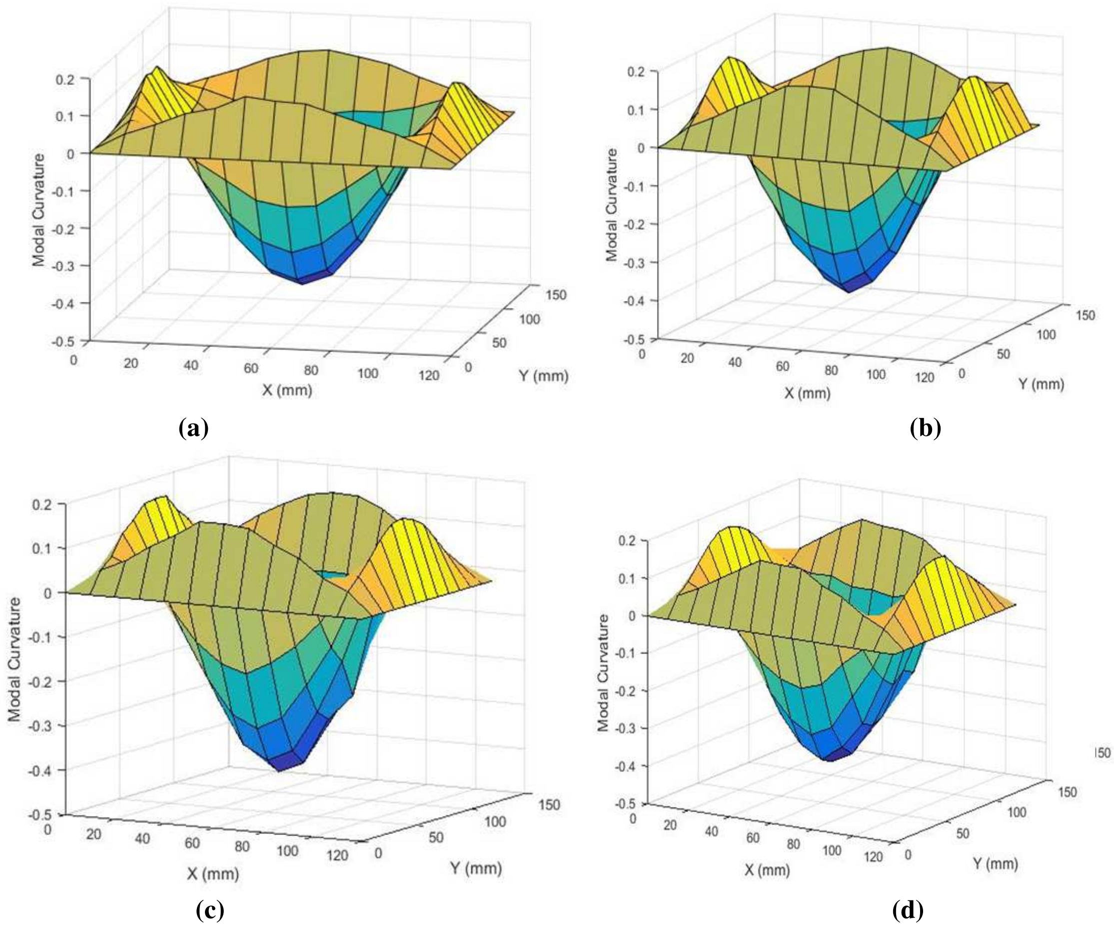
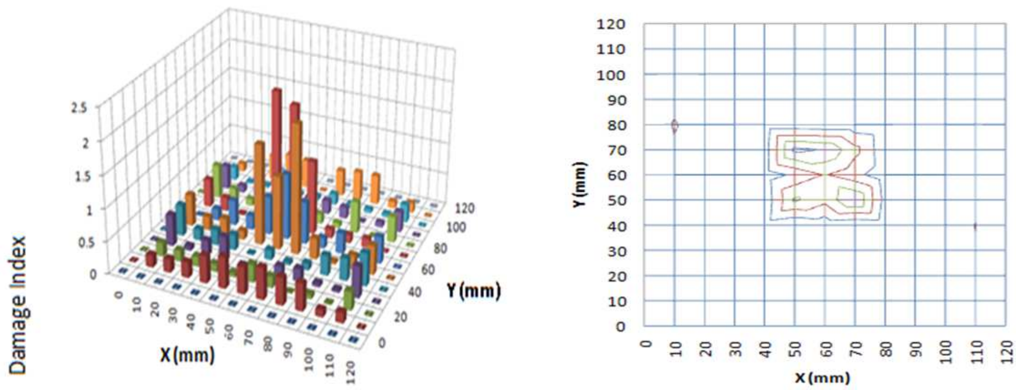


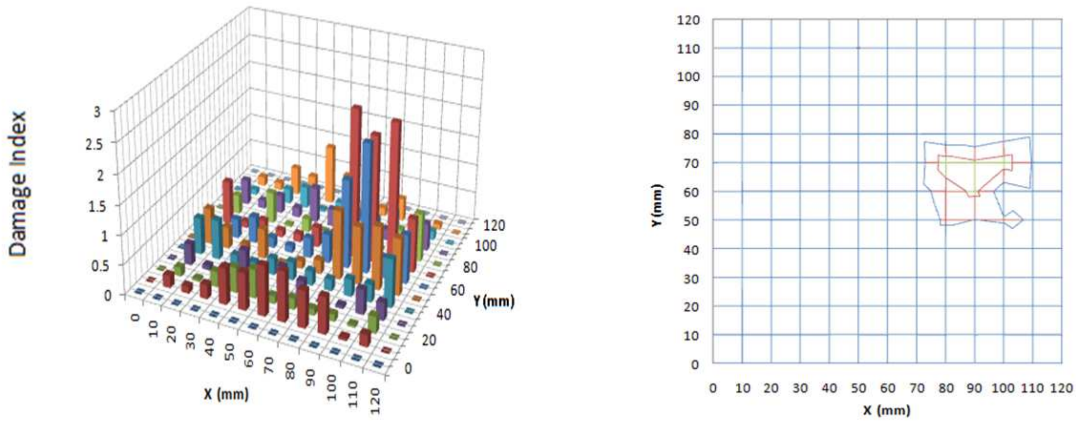
Figure 6: Modal Curvatures of Composite Plate, a) Intact b) Delamination at Center c) Delamination at Right side d) Delamination at NE Corner.

Mode shapes and Modal Curvatures of the delaminated composite plates are not sufficient to identify the delamination locations. The damage indexing method is developed by means of the absolute difference of modal curvatures of the intact with delaminated composite plates. Using mathematical equations (5) and (6) damage index of delaminated plates at each node is calculated. The damage indices and plan view of Normalized modal curvature of composite plates delamination at the center, right and northeast positions respectively shown in the following figures 7-9. The larger values of damage indices indicate the delamination position of the composite plate.



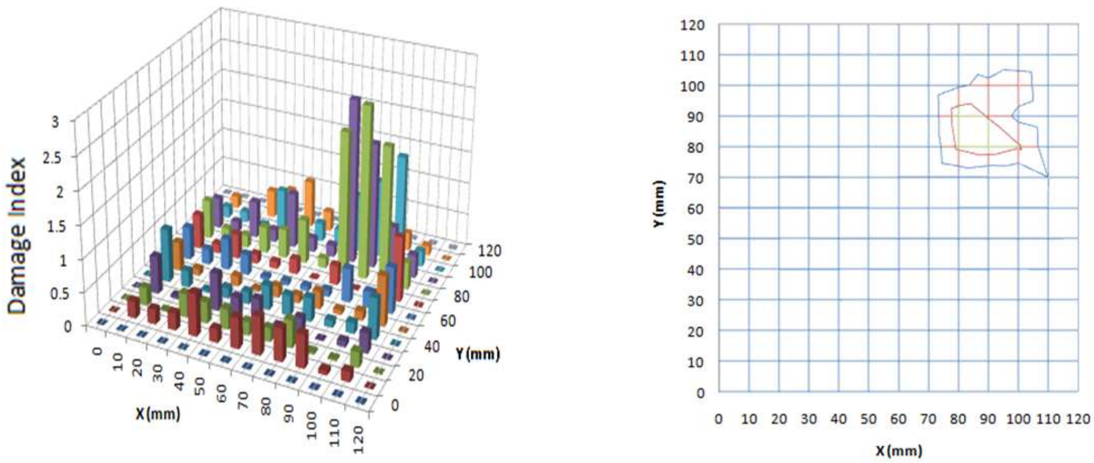
(a) (b)

Figure 7: Delamination at Centre, (a) Damage Index, (b) Plan form Normalized Modal Curvatures



(a) (b)

Figure 8: Delamination at Right, (a) Damage Index, (b) Plan form Normalized Modal Curvatures



(a) (b)

Figure 9: Delamination at NE, (a) Damage Index, (b) Plan form Normalized Modal Curvatures

Using the Plan form of the normalized modal curvatures of composite plates, delamination centers are estimated and shown in table 1.

Table 1: Actual, and Numerical Delamination Centers of Composite Plates

Sl. No.	Delamination Center			
	Actual		Numerical Method	
	X (mm)	Y (mm)	X (mm)	Y (mm)
1	60	60	60	60
2	90	60	90	60-70
3	90	90	80-90	90

4.2 Experimental Results

Modal analysis is performed on intact and three delaminated composites using an FFT analyzer, accelerometer, and impact hammer. At first natural frequency (for intact 2624Hz and delaminated 2602 Hz) FRF data is extracted for further analysis. The extraction window of FRF data using the FFT analyzer shown in figure 10.

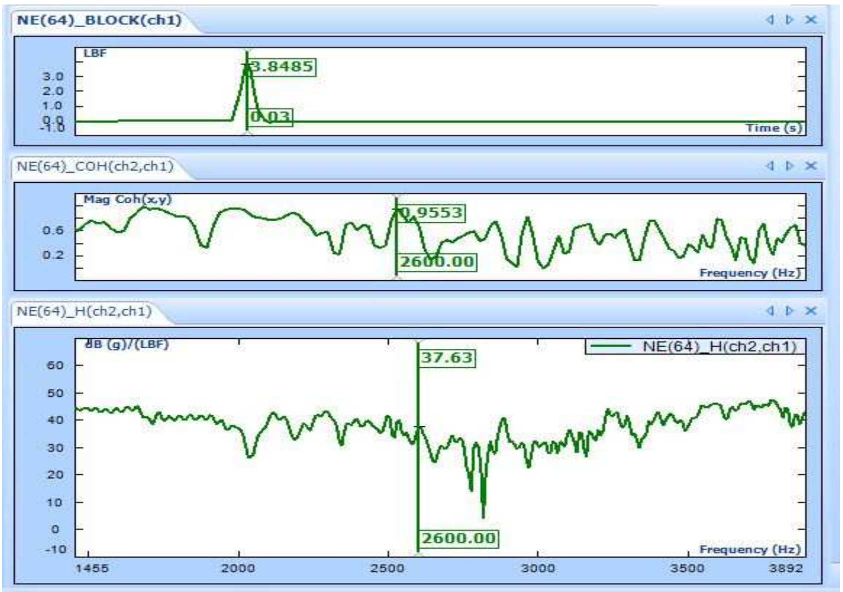


Figure 10: Impulse, Coherence and FRF Window of FFT Analyzer.

FRF data is extracted at each node of the composite plates. FRF is considered as a mode shape. Modal curvatures and Damage index are calculated using mathematical equations (2)-(6). The damage indices and plan view of Normalized modal curvature of composite plates delamination at the center, right and northeast positions respectively shown in the following figures 11-13. The larger values of damage indices indicate the delamination location of the composite plate.

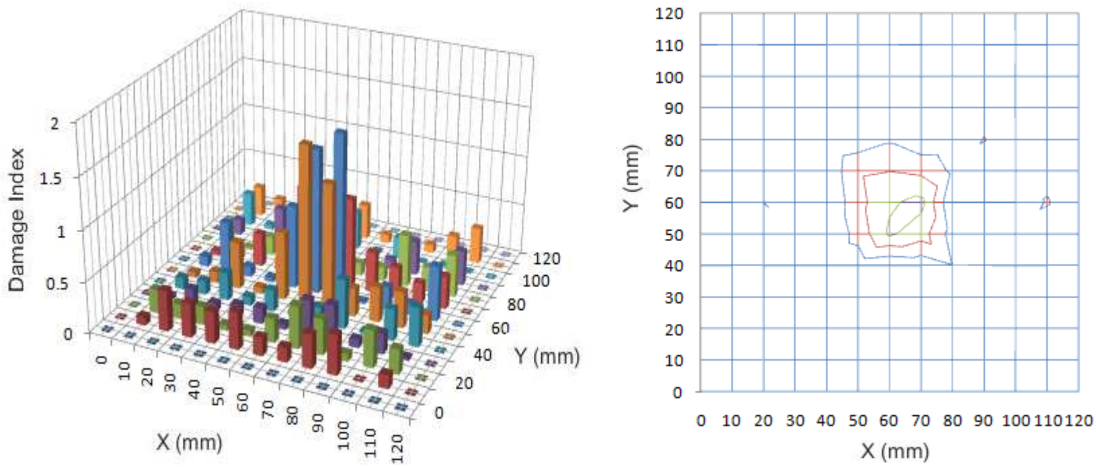
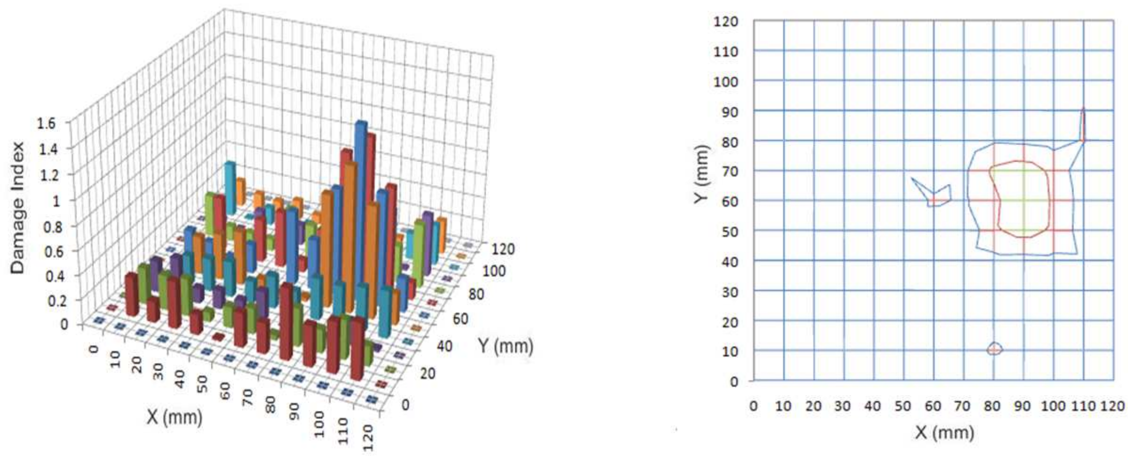
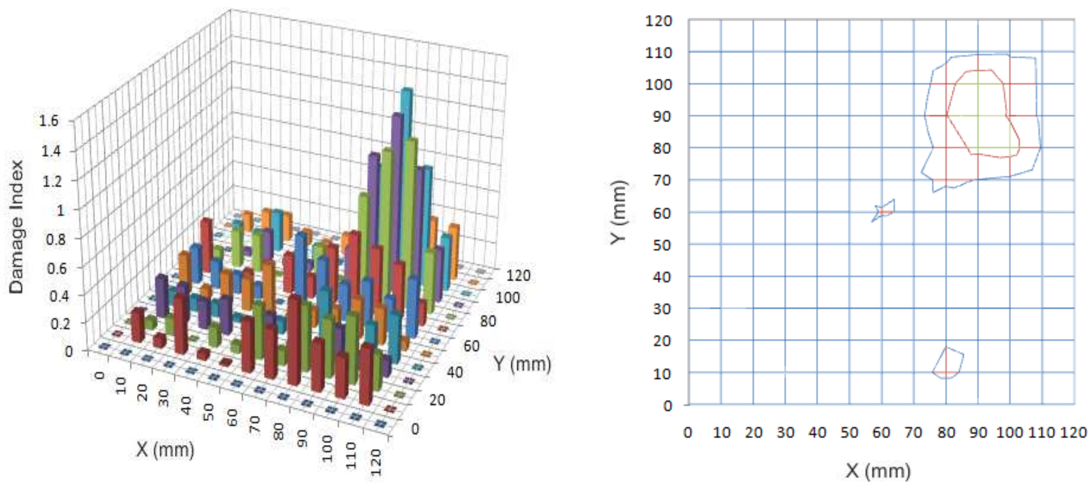


Figure 11: Delamination at Centre, a) Damage Index, b) Plan form Normalized Modal Curvatures.



(a) **(b)**

Figure 12: Delamination at Right, a) Damage Index, b) Plan form Normalized Modal Curvatures.



(a) **(b)**

Figure 13: Delamination at NE, a) Damage Index, b) Plan form Normalized Modal Curvatures.

Using Plan form of normalized modal curvatures of composite plates, delamination centers are estimated and shown in table2.

Table 2: The Actual and Experimental Delamination Centers of Composite Plates

Sl. No.	Delamination Center			
	Actual		Experimental Method	
	X (mm)	Y (mm)	X (mm)	Y (mm)
1	60	60	60-70	60
2	90	60	90	60
3	90	90	90	90

5. CONCLUSIONS

This paper presents the delamination position identification of composite laminates using normalized modal curvatures. Normalized modal curvatures are formulated using modal curvatures of the intact and delaminated composites. The composite plates with three delamination positions are analyzed by numerical and experimental modal analysis. The results from the numerical and experimental modal analysis and the subsequent conclusions are drawn and discussed as follows:

- Modal Curvature is a more prominent parameter than mode shape for minute singularities recognition in the composite plates.
- The proposed modal curvature based DI index method is successfully identifies the
- delamination location of the composite plates.
- This method is validated by performing Experimental and Numerical modal analysis.
- The proposed method is moreover used to detect multiple delamination (damages) of composite plates.

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